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Corn Canopy Resistance Determined from Whole Plant Transpiration

J.A. Tolk, T.A. Howell, J.L. Steiner, and D.R. Krieg¹

ABSTRACT

The crop resistance to vapor flux, or canopy resistance (r_c), of Penman-Monteith evapotranspiration (ET) equations has frequently been modelled by stomatal resistance measurements integrated to canopy level and the 'effective' portion of leaf area index (LAI_e) actively transpiring. This research evaluated the diurnal changes in r_c and a plant resistance (r_p) for full canopy, irrigated corn (*Zea mays* L.). They were calculated as a residual of an energy balance equation for vapor flux using lysimetrically measured ET for r_c and whole canopy transpiration (T) measured by sap flow gauges for r_p . LAI_e was calculated by $LAI_e = r_p / r_c$. During mid-day when T fluxes dominated ET, r_c and r_p values were generally within 20 $s\ m^{-1}$ of each other. Low light levels of early morning and late afternoon increased r_p compared with r_c , resulting in a greater reduction in T than in ET and a changing LAI_e . We modelled r_c (r_{cpred}) as $r_{cpred} = r_{ppred} / LAI_e$, where r_{ppred} was r_p described as a function of solar radiation (R_s) and LAI_e was the daily mean. The non linear model for r_{ppred} was $r_{ppred} = 333.9 - 9.5 * R_s^{0.5}$ ($r^2 = 0.70$, $RMSE = 50.2\ s\ m^{-1}$). Average LAI_e was 1.34 (± 1 SD of 0.2 to 1 LAI_e), or about 30% of maximum LAI . When r_{cpred} was compared to r_c , it produced the relationship of $r_c = 20.8 + 0.78 r_{cpred}$ ($r^2 = 0.68$, $RMSE = 30.2\ s\ m^{-1}$). While R_s can partially model r_c , the diurnal changes in LAI_e should also be considered.

Keywords: Evapotranspiration, Crop-water use, Plant modelling

INTRODUCTION

The Penman-Monteith formula (Monteith, 1965) for evapotranspiration (ET, in $mm\ h^{-1}$) incorporates a surface or plant canopy resistance (r_c , in $s\ m^{-1}$) to vapor flux. This resistance has often been characterized by bulk stomatal resistance (r_s , in $s\ m^{-1}$), calculated from the mean stomatal resistance of component leaves (sunlit and shaded) treated in parallel that has been adjusted to canopy level by leaf area index (LAI) (Szeicz and Long, 1969). Monteith (1981) noted, however, that it was not evident whether r_c depended mainly on stomatal components or whether it contained other factors, such as an aerodynamic element. Berkowicz and Prahm (1982) pointed out that r_c depended on both the degree of stomatal opening (stomatal resistance) and the resistance at the soil surface based on its water content. Hatfield (1985) and Van Bavel (1967) also noted the effect of soil profile water content on stomatal behavior.

Berkowicz and Prahm (1982) pointed out the difficulty of building an r_c value representative of a crop canopy from measurements of r_s . Szeicz and Long (1969) combined r_s with 'effective'

¹Authors are Plant Physiologist, Research Leader (Agric. Engr.), USDA, ARS, Bushland, TX; Research Leader (Soil Scientist), USDA, ARS, Watkinsville, GA; and Professor, Dept. of Plant and Soil Science, Texas Tech University, Lubbock, TX.

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leaf area index (LAI_e) which recognizes that, in a fully-developed canopy, the lower leaves may not be illuminated well enough for the stomata to fully open.

Szeicz et al. (1973) and Hatfield (1985) isolated r_c by calculating it as a residual of energy balance equations in which latent heat flux was estimated. Direct measurement of water vapor fluxes can be made with lysimeters for total ET. Sap flow gauges (Baker and Van Bavel, 1987) measure mass flux of water through the whole plant which approximates transpiration (T , in mm h^{-1}). These gauges eliminate the need for integration of individual leaf stomatal resistance measurements to a whole canopy level. By partitioning water vapor fluxes into exclusively plant resistance (r_p , in s m^{-1}) calculated from T , and soil and plant resistances (r_c) calculated from ET using the residual method, we examined the roles of plant, soil, and environmental factors in each. The objective of this research was to examine the diurnal trends in r_c and r_p and to model these resistances using environmental and plant parameters.

METHODS AND MATERIALS

Corn (*Zea mays* L., hybrid Pioneer 3124) was grown in 1990 at the USDA Conservation and Production Research Laboratory at Bushland, TX. The crop was sown on Day of Year (DOY) 129 in 0.76-m east-west rows for a population of approximately 6 plants (m^{-2}). The cropped area was adequately fertilized prior to planting; weeds were controlled throughout the season. While the cropped area was frequently irrigated (total of about 600 mm) using a lateral move sprinkler system, some water deficits occurred in the latter part of the season. A weighing lysimeter was located in the center of two contiguous 5-ha fields with unobstructed fetch around each lysimeter. Each lysimeter had a 9- m^2 surface area, a 2.3-m depth, and contained monolithic soil cores of Pullman clay loam (fine, mixed, thermic Torricic Paleustoll).

Transpiration was estimated using four to nine sap flow gauges that were attached to plants located on the lysimeters. The monitoring period was from late vegetative (DOY 200) growth stage through early dent (DOY 250). Mean mass sap flux was converted to transpiration flux ($\text{kg h}^{-1} \text{m}^{-2}$) on an areal basis by multiplying the plant density (p m^{-2}) by the mean mass sap flux ($\text{kg h}^{-1} \text{p}^{-1}$).

The vertical gradients of vapor pressure and temperature as well as plant and aerodynamic resistances which control the latent heat flux from plant and soil can be described as (Choudhury, 1989)

$$\lambda ET = [\rho C_p (e_s - e_a)] / [\gamma (r_{av} + r_c)] \quad (1)$$

where λ is the latent heat of vaporization (J kg^{-1}), ρ is the density of air (kg m^{-3}) at constant pressure, C_p is the specific heat of air ($1004.8 \text{ J kg}^{-1} \text{ K}^{-1}$), e_a is ambient vapor pressure (kPa), e_s is saturated vapor pressure at canopy temperature (C), γ is the psychrometric constant (kPa C^{-1}), and r_{av} is aerodynamic resistance (s m^{-1}) to vapor exchange. For this calculation, aerodynamic resistance to heat exchange (r_{ah} , in s m^{-1}) and r_{av} were assumed to be equivalent, and the r_{ah} equation presented by Hatfield (1985) and evaluated by Tolck et al. (1995) was used. Equation [1] can be rearranged to solve for r_c as

$$r_c = [\rho C_p (e_s - e_a) / (\gamma \lambda ET)] - r_{ah} \quad (2)$$

Equation [2] was adapted to represent plant resistance (r_p , in s m^{-1}) as measured by the sap flow gauges by substituting λT for λET and r_p for r_c , respectively, and assuming the same r_{ah} . For comparison purposes, both r_c and r_p were calculated from 0830 to 1930 during which transpiration was occurring.

Szeicz and Long (1969) presented

$$r_c = r_l / LAI_e \quad (3)$$

where all leaves were considered effective in transpiration until LAI reached 0.5 of the maximum value (LAI_m) after which it remained $LAI_e = 0.5 LAI_m$. This equation was modified to

$$LAI_e = r_p / r_c \quad (4)$$

where ($r_p = r_l$) so LAI_e could be calculated from the two resistances.

RESULTS AND DISCUSSION

Sixteen days were selected for analysis which represented the time period of full cover through early senescence. They began on DOY 209, just prior to anthesis on DOY 213, and continued through early dent growth stage on DOY 249. An example of diurnal changes in r_c , r_p , and solar radiation (R_s , in W m^{-2}) is presented for DOY 211 (Fig. 1), which was three days after an irrigation. During the time period presented (0830 to 1930 CST) during which T was occurring, total ET was 4.64 mm, of which 80% (3.72 mm) was T and 20% (0.92 mm) was soil water evaporation (E , in mm h^{-1}). About 73% of the total ET occurred during mid-day (1000 to 1530 CST), when r_c and r_p were almost identical and T losses were 86% of ET. However, during morning (0830-1000) and afternoon (1530-1930) hours, r_p was considerably higher than r_c , when T dropped to about 68% of ET. This suggests some stomatal closure due to lower light levels. E was fairly constant from morning through afternoon at 0.08 mm h^{-1} . For the time period presented, mean r_c was 81.7 s m^{-1} and r_p was 128.7 s m^{-1} . Average soil water evaporation for the 16 days was 14% of the ET from 0830 to 1930 CST, but was as much as 30% following irrigation or rainfall, similar to data presented by Villalobos and Fereres (1990).

During the 40 day period analyzed, LAI ranged from a maximum of 5.6 to a minimum of 4.3 (Fig. 2). Using diurnal r_c and r_p values, LAI_e values were calculated using equation [4] which produced a mean value for the season of 1.34, but with ± 1 SD of .2 to 1 LAI due to the changing relationship between r_p and r_c during the day (Fig. 1). An equation presented by Tanner and Sinclair (1983) calculated the amount of LAI exposed directly to radiation as 1.4 for $LAI > 3$. Effective LAI was about 30% of the maximum.

Since plant stomata control most of the water flux through plants (Jones, 1983), various parameters controlling stomatal activity such as solar radiation, PAW, vapor pressure deficit, and LAI have been used to model stomatal resistance (Stewart, 1988). We developed a simple predictive relationship for r_p (r_{pred}) using R_s in the form $r_p = 333.9 - 9.4 R_s^{0.5}$ ($r^2 = 0.70$, $RMSE = 50.2 \text{ s m}^{-1}$) (Fig. 3). The relationship was analyzed using a nonlinear ordinary least squares procedure (PROC MODEL, SAS Institute, 1988) which returned a best fit using a square root

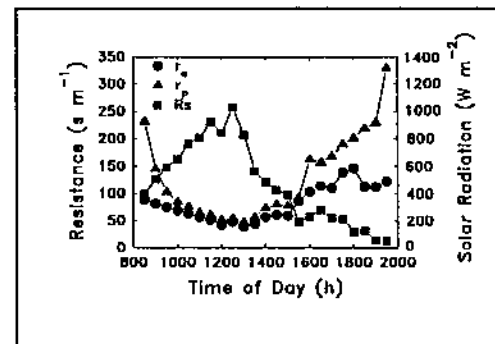


Figure 1. Diurnal trends in canopy resistance (r_c), plant resistance (r_p), and solar radiation (R_s) for DOY 211.

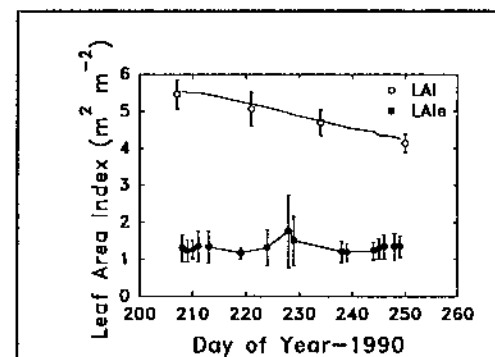


Figure 2. Seasonal changes in measured leaf area index (LAI), and calculated effective LAI_e with ± 1 SD.

function. The curve of Fig. 3 shows a changing resistance through all R_s levels, unlike the exponential curves of Hatfield (1985) and Stewart (1988) which indicate an almost constant r_c at $R_s > 400 \text{ W m}^{-2}$. Since r_p incorporates a whole canopy response, the curve of Fig. 3 possibly reflects the diurnal changes in canopy illumination.

We developed a model for predicted r_c (r_{cpred}) based on equation [3], using r_{ppred} for r_l and an LAI_c of 1.34. When compared to lysimetrically measured r_c , the relationship was $r_c = 20.8 + 0.78 \cdot r_{cpred}$ ($r^2 = 0.68$, $RMSE = 30.2 \text{ s m}^{-1}$). At least part of the error in this approach is due to the changing diurnal relationship between r_p and r_c (Fig. 1), resulting in high LAI_c in the morning and late afternoon. This is unlike conclusions of Kjelgaard et al. (1994), who evaluated corn r_c using equation [3] where r_l remained constant and LAI_c was either held constant or was allowed to vary diurnally. They determined that both a constant r_l and LAI_c was sufficient for short term calculations of ET.

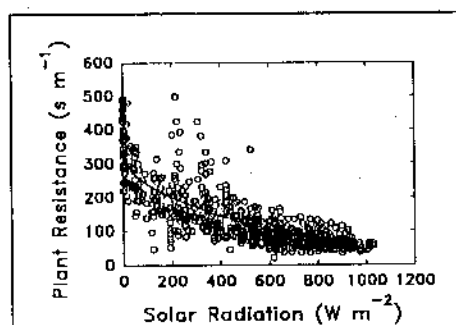


Figure 3. The relationship between solar radiation and plant resistance.

CONCLUSIONS

Calculation of r_p from whole plant transpiration represents a viable alternative to the calculation of r_l from LAI and individual stomatal measurements because it bypasses the need to create a strategy to integrate point measurements to the canopy level. Plant resistance approximates r_c only during midday hours. During morning and afternoon when 30% of day-time ET can occur, r_p can be more than twice that of r_c which also causes LAI_c to vary diurnally. With a fully developed canopy under minimum water stress, solar radiation and a constant LAI_c can partially model r_c . Ignoring the marked diurnal changes in r_c and r_p and consequently LAI_c , however, can lead to overestimation of r_c , and the underprediction of ET.

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